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# On opportunities and threats to conserve the phylogenetic diversity of Neotropical palms

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## Abstract

**Aim:** Palms are an ecologically and societally important plant group, with high diversity in the Neotropics. Here, we estimated the impacts of future climate change on phylogenetic diversity (PD) of Neotropical palms under varying climatic and dispersal scenarios, assessed the effectiveness of the established network of protected areas (PAs) for conserving palms PD today and in 2070, and identified priority areas for the conservation of palm species and their evolutionary history in the face of climate change.

**Location:** Neotropics.

**Methods:** We used ecological niche modelling to estimate the distribution of 367 species in the present and for 2070 based on two greenhouse gas emission and two dispersal scenarios. We calculated Faith's PD within each five arc-minute grid cell to evaluate the effectiveness of PAs relative to null models and used phylogenetic spatial prioritisation analysis to detect priority areas.

**Results:** We found that even under the most optimistic climatic and dispersal scenarios, the established network of PAs performed poorly in safeguarding palms PD under both current conditions and those projected for 2070. Significant losses in PD inside PAs are expected under future climate conditions, especially if species are unable to disperse to suitable areas. Nevertheless, a modest and strategic increase in the number of PAs could considerably improve the protection of palms PD in the present and 2070.

**Main conclusions:** The PD of Neotropical palms is poorly represented within the established network of PAs, at both present and in 2070. A higher realised dispersal rates would diminish PD losses inside the network of PAs. The conservation of palm PD can be improved through the expansion of PAs in strategic regions such as the upper portion of the Amazon Basin, Tropical Andes and Mesoamerica.

**KEYWORDS**

climate change, dispersal, evolutionary history, species distribution models, systematic conservation planning, Zonation

## 1 | INTRODUCTION

Human-induced changes in natural ecosystems have become increasingly intense in tropical and subtropical regions (Hansen et al., 2013), causing biodiversity loss (Newbold et al., 2015), reducing ecosystem service provisioning (Hautier et al., 2015) and affecting human well-being (Pecl et al., 2017). The adverse effects of land-use change are likely to be exacerbated by the ongoing climate change (Blach-Overgaard et al., 2015; Zhang et al., 2017), which is already affecting species and communities worldwide (Pecl et al., 2017; Steinbauer et al., 2018). Species' response to climate change may include shifts in geographical distribution, adaptation to new conditions or extinction (Jezkova & Wiens, 2016; Lenoir & Svenning, 2015).

Conservation planning exercises commonly aim to identify priority areas for the establishment of protected areas (PAs), one of the main strategies used to protect biodiversity worldwide (CBD, 2010; Thomas et al., 2012). Over the last decades, the number and extent of PAs have rapidly increased, covering now 15% of the world's terrestrial and inland water surface areas (UNEP-WCMC et al., 2018). However, such growth has not necessarily increased species protection as PAs have been systematically biased towards remote and unproductive places (Baldi et al., 2017; Joppa & Pfaff, 2009; Vieira et al., 2019). In addition to such biases, climate change is rarely considered in the establishment of PAs (Jones et al., 2016), which could result in PAs that may not adequately protect biodiversity against this pressure (Araújo et al., 2011; Baldi et al., 2017; Joppa & Pfaff, 2009; Monzón et al., 2011). Therefore, a strategic selection of new PAs robust to climate change is important to improve species current persistence and under future climate change (Pressey et al., 2007).

Conservation decisions are usually focused on animals, despite the crucial importance of plants for maintaining life on Earth (Corlett, 2016). Among the many plant species under threat (Pitman & Jorgensen, 2002), focusing efforts on those that play important ecological and economic roles may be strategic (Blach-Overgaard et al., 2015; Corlett, 2016; Idohou et al., 2017). In the Neotropics, palms (Arecaceae) constitute an ecologically and economically important plant family with around 790 species (Balslev et al., 2011). Palm species play fundamental ecological roles such as the provision of food and shelter for several animal species and are an important source of food and materials for people at local and global scales (Cámara-Leret et al., 2017; Dransfield et al., 2008; Henderson, 1986; Howard, 2001; Laureto & Cianciaruso, 2017; ter Steege et al., 2013; Zona & Henderson, 1989).

The distribution of palm species is strongly influenced by the climate (Blach-Overgaard et al., 2010; Vedel-Sørensen et al., 2013), and the effects of climate change on a restricted number of palm species have already been investigated (Idohou et al., 2017). In addition to climate conditions, edaphic factors are determinant of palm distributions (Bjorholm et al., 2008; Eiserhardt et al., 2011). Future changes in climate and land-use are predicted to reduce seed plant diversity, posing a greater threat for evolutionarily distinct species (Zhang et al., 2017). Therefore, studies comprising more palm species and considering the combined effect of climate, soil and land-use are fundamental for providing a comprehensive picture of future threats for this important plant group and enhance the effectiveness of conservation strategies.

The importance of biodiversity aspects beyond species richness for prioritising areas for conservation or evaluating PA network effectiveness is increasingly recognised (Cadotte & Tucker, 2018; Pollock et al., 2015; Rosauer et al., 2017), notably in terms of species' phylogenetic and functional diversity (Pollock et al., 2015; Quan et al., 2018). Specifically, the use of phylogenetic diversity (PD) enables quantification of species evolutionary history throughout geographical space and time, as well as its concentration, replacement and loss (Cadotte & Davies, 2010). In this sense, the use of PD in conjunction with the traditional species-based approach represents an advance in assessing the conservation value of an area (Faith, 1992; Veron et al., 2017). Protecting PD is already part of important conservation initiatives such as the Aichi Targets (target 13, specifically; CBD, 2010). In fact, preserving the PD of species with significant economic and social roles—the case for palms—constituted one of the conservation targets to be achieved by 2020 (CBD, 2010).

Achieving successful protection of palms PD in the present and future requires a broad view of conservation planning. Limited use of scientific criteria for the real-world establishment of PAs has resulted in limited connectivity between them and a large number of palm evolutionary lineages without protection. This undermines the effectiveness of the PA network for conserving the phylogenetic tree of palms under climate change. In the context of the present study, the word 'effectiveness' is defined as the ability of a PA to retain higher PD than would be randomly expected. We investigated if the current Neotropical PA network is effective for conserving palm PD at both the present and in 2070, towards the end of the 21st century. To do so, we answered the following questions:

(i) How much PD is represented in the established network of PAs, and how could it change by 2070 under alternative climate change and dispersal scenarios?
(ii) What is the effectiveness of current PAs for conserving the PD of palms for different climate change and species' dispersal scenarios?
(iii) In which regions should new PAs be created for conserving the PD of palms under current and future conditions?

## 2 | METHODS

### 2.1 | Study area

Our study area encompasses the Neotropics (−34°55' and 32°39' latitude), a region ranging from the middle of Chile and Argentina to northern Mexico, encompassing 37 countries and > 200 ecoregions (Olson et al., 2001). The Neotropical region stands out for its high

diversity of plants, many of which are endemic and rare (Brummitt et al., 2020; Enquist et al., 2019). Several biodiversity hotspots are in the Neotropics, reflecting its high biodiversity and great pressure on its natural environments (e.g. the Atlantic Forest, Tropical Andes or Mesoamerica; Myers et al., 2000).

## 2.2 | Occurrence records and data cleaning

We obtained occurrence records for palm species inhabiting the Neotropical region from the GBIF, speciesLink, Plants of Bolivia and BIEN databases (Table S1). We checked, corrected, and updated species names using the TNRS v4.0, ThePlantList v1.1 and Tropicos (Table S1, see occurrence data cleaning in Appendix S1). Environmental filters were also used for correcting sampling bias (Appendix S1). We only included species with ≥ 10 independent records after cleaning in the subsequent analyses (van Proosdij et al., 2016), resulting in a total of 42,481 occurrences for 461 palm species. However, we kept in our final database only species with a high model performance, totalling 367 species (details are described in the section 'Ecological niche models').

## 2.3 | Current and future environmental data

We used 19 bioclimatic variables for current (1950–2000) and future (2070) conditions available at the WorldClim 2.0, in conjunction with edaphic data for creating ecological niche models (ENMs; Tables S1 and S2). We used six edaphic variables related to physical properties (e.g. sand, silt and clay concentration) provided by the SoilGrids 2.0. Including edaphic data in ENMs for plants may increase model performance (Velazco et al., 2017), reflecting the importance of soil conditions for plant species distributions (Eiserhardt et al., 2011). Climatic and edaphic spatial data were standardised to a five arc-min resolution. A principal component analysis was performed on the original environmental variables (soil and climate) based on a correlation matrix. The eigenvectors were used to calculate the scores of the first nine derived principal components, which were used as new predictors variables (representing 95.3% of the total variance; De Marco & Nóbrega, 2018) for creating the ENMs for all species (Table S3). The same eigenvectors were used to calculate the scores of the principal components for future environmental scenarios (2070).

We evaluated the effect of climate change on palm species distribution using two Representative Concentration Pathways (RCP4.5 and RCP8.5), an optimistic and business-as-usual scenario of climate change, respectively. A projection of climate change for 2070 was used based on five Global Circulation Models (GCMs) sourced by the CCAFS-Climate database (Table S1). The following GCMs were used: CESM1-BGC, FIO-ESM, GFDL-ESM2G, GISS-E2-R and MOHC-HADGEM2-ES. The choice of the GCMs was based on previous analysis using 28 GCMs performed for the same extension and RCPs for 2050 (Velazco et al., 2019).

## 2.4 | Ecological niche models

A plethora of algorithms are used to predict species distribution based on different statistical approaches and data input (e.g. presences, absences, background points). Algorithm performance varies depending on the modelling condition (e.g. species range, niche breadth, number of records, data type; Norberg et al., 2019; Qiao et al., 2015) and is one of the primary sources of model uncertainty (Thuiller et al., 2019). Therefore, the use of several algorithms allows detecting which are the best for a particular study (or species), as well as reporting model uncertainty (Norberg et al., 2019; Thuiller et al., 2019). We used seven algorithms encompassing a range of statistical techniques for modelling species distributions (see Appendix S2 for details). An approach using ensembles of small models was used for those species with <90 cleaned occurrences (i.e. species with <10 record by predictors; Breiner et al., 2015) in order to avoid model overfitting (Appendix S3). Model performance was evaluated using spatial block cross-validation to control the potential spatial autocorrelation between training and testing data (Roberts et al., 2017). For this, 20 grids were generated with resolutions ranging from 0.5 to 10 degrees and the optimal grid-size for each species were selected that showed (i) the lowest spatial autocorrelation, (ii) the maximum environmental similarity and (iii) the minimum difference of numbers' records between training and testing data (Velazco et al., 2019). For species with no optimal grid-size, we used a conventional k-fold cross-validation approach instead. We used the True Skill Statistic (TSS), a commonly used threshold dependence index, to evaluate model performance (Allouche et al., 2006), only using models with a TSS ≥ 0.4 ($n$ = 367 species).

The final ENM for each species was created based on the ensemble forecast procedure calculated by the arithmetic average of the suitability predicted by the best algorithms for each species, that is models with performance greater than or equal to the algorithms' average TSS. For future conditions, after performing the ensemble forecast to construct a single consensus model of the algorithms for a given GCM, a new average of suitability values among the five GCMs was conducted to obtain the final future projection. We used the threshold that maximises the sum of the sensitivity and specificity to binarise models (Liu et al., 2011) to facilitate combining the ENMs and the branches of the phylogenetic tree (see Phylogenetic spatial conservation planning). Such thresholds were calculated based on the suitability values of the ensemble model of each species under current conditions and then used for binarising current and forecasted models.

Projection of ENMs throughout the study region can predict suitable areas far from the species' geographical domain (Velazco et al., 2020). To delimit species distribution under the current condition and avoid models' overprediction, models were trimmed based on the area encompassed by a minimum convex hull polygon determined by species records plus a buffer zone of 100 km surrounding the edges of convex hull polygons (Kremen et al., 2008; Mendes et al., 2020). We used Mobility-Oriented Parity to detect and correct

models' extrapolation under future scenarios (see Appendix S4 for details; Owens et al., 2013). A variance partitioning approach was used to measure uncertainties on the distribution of PD in the future from alternative algorithms, GCMs, and RCP (Appendix S5; Thuiller et al., 2019). Modelling pre- and post-processing were performed with the ENMTML R package (Andrade et al., 2020).

## 2.5 | Dispersal scenarios

Species dispersal through landscape mosaics regulates the species' ability to track climate change and access newly suitable areas (Midgley et al., 2006). Therefore, considering species dispersal ability is key for evaluating climate change effects on species distributions. In order to evaluate a wide range of possible outcomes, two scenarios of species dispersal were assessed: (i) negligible dispersal, that is species, will persist only in areas where the present estimated distribution and future suitable conditions overlap; and (ii) human-assisted dispersal, with 50 km/decade into expected novel suitable areas (Payne & Bro-Jørgensen, 2016). This assisted dispersal could consist of moving a species' individual or propagules from their current locations to regions that are and will remain suitable under climate conditions (Schwartz et al., 2012; Vitt et al., 2010). Considering the variety of uses attributed to palms by human populations (Haynes & McLaughlin, 2000; Laureto & Cianciaruso, 2017; Macía et al., 2011), the second scenario incorporating human assistance on palms dispersal is relevant for providing a more comprehensive picture of climate change effects on palm species. The second dispersal scenario was constructed by extending species occurrence from the border of current species distribution, delimited by loss of natural land cover (see below), up to 350 km (Blach-Overgaard et al., 2015).

## 2.6 | Phylogenetic diversity

We used a species-level phylogeny of Arecaceae for performing the phylogenetic analysis (Faurby et al., 2016). Given that five species in the database used were absent from this phylogenetic tree, species were added as polytomies within their respective genus (Revell, 2012). We removed all species not included in our analysis from the phylogeny, resulting in a phylogenetic tree composed of 367 species. We calculated the phylogenetic diversity of palms species based on the Faith's Phylogenetic Diversity index (PD) that consists of the summed lengths of the phylogenetic branches of a species set (Faith, 1992).

## 2.7 | Land-use data

We used a layer of remaining natural vegetation obtained from the Climate Change Initiative of the European Space Agency (ESA; Table S1) for the year 2015 at a resolution of 300 m. We reclassified the 37 land cover categories into natural and anthropogenic land-use (Table S4). The proportion of remaining natural cover in each five arc-min cell was calculated as the ratio between the number of cells of 300 $m^2$ presenting natural cover divided by the total number of cells. As the critical point of habitat loss where species would experience local extinction may differ among taxa (Swift & Hannon, 2010), for simplicity here, it was assumed that cells with less than 50% natural vegetation would be unsuitable for species persistence (Eriksson & Kiviniemi, 1999; Montoya et al., 2010; Rigueira et al., 2013). We did not use future land-use such as those available in the Land-use harmonisation database (https://luh.umd.edu) because of their inconsistency with the ESA database regarding methodological approaches, resolution and land-use classes (see Appendix S6).

## 2.8 | Effectiveness of protected areas

We obtained data on PAs from the World Database on Protected Areas (Table S1, see Appendix S7 for further information about PAs dataset processing). A total of 2,135 PAs distributed in 26 countries were included in the final dataset. We estimated PD changes in each PA by calculating the average PD difference between current and future conditions based on grid cells encompassed by each PA. Calculations were made for both the whole study area and for each country, separately.

We used a null model approach to test PA effectiveness; that is, the ability of a PA to retain higher PD than would be expected by chance. To do so, each PA was randomly redistributed 999 times with geopolitical restriction (i.e. each PA was relocated only within the country in which it belongs) while maintaining its area, orientation and shape (Ribeiro et al., 2016). At each randomisation run, the mean value of PD was calculated based on the cells encompassed by each PA, for current and future scenarios. PAs were scored as effective if their mean PD was at least in the 95th percentile of the frequency distribution of the corresponding PD values expected by chance (i.e. PAs with $p < .05$). We calculated the relative proportion of effective and non-effective PAs for the entire Neotropics region and each country separately. The relative geographical extension covered by the effective and non-effective PAs was also calculated, hereafter weighted proportion, by calculating the ratio between the sum of geographical extension covered by effective protected area and the sum of the area covered by the total PA network for a determined region (whole study area or each country). We used R software v.3.5.0 (R Core Team, 2018) to create ENMs and for data processing and analyses (Appendix S8).

## 2.9 | Phylogenetic spatial conservation planning

Priority areas were identified for the conservation of the palm phylogenetic tree under current and future conditions based on a phylogeny-based prioritisation analysis in which the conservation features are branches of a phylogeny (Pollock et al., 2015, 2017; Rosauer et al., 2017). The geographical expression of branches of

the phylogeny followed the Pollock et al. (2015) approach. Thus, the distribution of a branch was constructed by combining the distributions of descendent species of this branch (i.e. assuming that a branch is present in a cell if any of its descendants occur in that cell). Each branch received a weight proportional to its length (Pollock et al., 2017), so that larger branches have a higher relative importance in the prioritisation analysis. We also accounted for the uncertainty of phylogenetic branches (resulting from uncertainties in species distribution) in prioritisation analysis aiming to achieve a robust conservation decision by using the info-gap component in Zonation. To do so, we calculated the geographical distribution of branches based on species distributions resulted from alternative ENMs algorithms and GCM. Uncertainty layers were based on the standard deviation between algorithms only and between algorithms and GCM, for current and future condition, respectively.

The Zonation v.4.0 software was used for all spatial prioritisations. Zonation produces a ranking of all cells of the study region from high to low based on complementarity and irreplaceability (Moilanen et al., 2005). We choose to use the core-area Zonation removal rule, which emphasises the selection of areas of high suitability for the rarest or high-weighted branches (i.e. higher evolutionary history) instead of areas of high PD. Thus, a cell receives high conservation value if it contains a large proportion of a branch distribution regardless of branch richness in that cell. We included in the analyses the PA network already established in the Neotropics as a mask in Zonation; that is, existing PAs were accounted for as high priority in the solution produced (Appendix S9; Moilanen et al., 2014).

For each scenario, we evaluated the current and future representativeness of palm PD in the PA network and priority areas together covering 5%, 10% and 17% of the total landscape beyond the total area covered by PAs (i.e. conservation targets). The first and second conservation targets are frequently used to show the top-ranked areas (Pollock et al., 2015, 2017). The last conservation target follows Aichi Target 11, which states that 17% of terrestrial and inland water surface must be protected by 2020.

## 3 | RESULTS

We modelled the distribution of 367 Neotropical palm species, representing c.55% of the total number of Neotropical palm species. Overall, models had high TSS values for all species and algorithms, with a mean of 0.50 and a standard deviation of ± 0.22 (Figure S1). We found that the algorithms are the main source of uncertainty that determines changes in PD under future conditions, followed by GCM and RCP (Figure S2).

Under current climate conditions and remaining natural vegetation (2015), we found that higher values of palm PD are concentrated in a region ranging from Costa Rica to eastern Peru and southern Colombia and Venezuela, and into the upper portion of the of Amazon Basin (Figure 1). Most PAs are distributed in regions of medium to low palm PD, while the areas with the highest PD values are largely unprotected (Figure 1).

Estimated future palm PD inside the existing network of PAs varied according to the different dispersal scenarios independent of the RCP used (Figure S3). Overall, PD was reduced under negligible dispersal scenarios. Under the human-assisted dispersal scenario, a balance of gains and losses with a slight tendency to PD gain was observed.

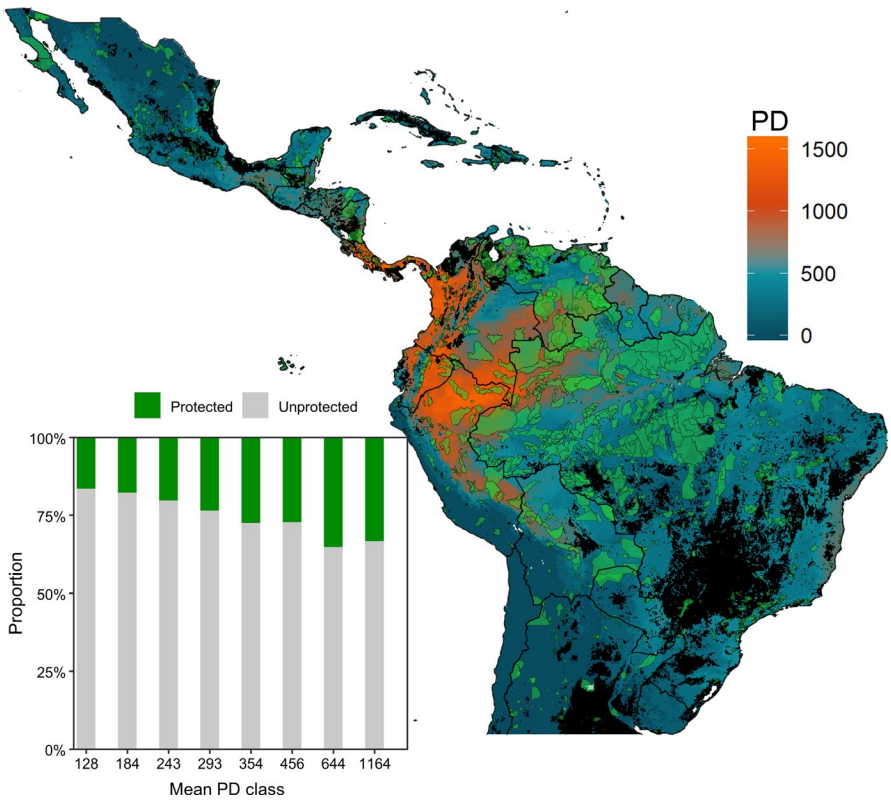


**FIGURE 1** Current phylogenetic diversity (PD) pattern of Neotropical palms and its coverage by protected areas. Green polygons depict protected areas, while black areas depict cells with less than 50% remaining natural vegetation. The histogram shows the relative proportions of protected and unprotected areas for different intervals of phylogenetic diversity classes

While comparing the mean PD values in each PA between the current and future conditions, >75% of PAs are expected to lose PD under the negligible dispersal scenario. In contrast, there was an increase in mean PD within PAs under the human-assisted dispersal scenario, regardless of the RCP considered (Figure S4). At the country level, similar patterns as those for the whole study area were found (Figure S5).

We found that < 12% of PAs are considered effective in the current period, that is harbour more PD than expected by chance (Figure 2a and S6). Those areas account for c.25% of the total area covered by PAs (Figure 2b) and are placed in western Amazonia, southern Mexico and Central America (Figure S6). Interestingly, ineffective PAs in the current period tended to remain ineffective in 2070. This result highlights that the increasing PD in existing PAs under some future scenarios (Figure S3) is not linked to a substantial increase in the number or extent of effective PAs (Figure 2).

When considering the effectiveness of PAs at the country level, <25% of PAs in each country were effective (Figure S7a). A more heterogeneous pattern was found when weighting the proportion of effective and non-effective PAs by the area occupied by PAs in each country, with few countries having > 50% of their PAs considered effective (Figure S7b). Under future climate conditions, despite a small increase in the number of effective PAs under a favourable dispersal scenario, most PAs were considered ineffective, with few countries presenting ≥ 50% of their PAs as effective (Figure S8).

Phylogenetic spatial prioritisation analysis highlighted that priority areas for conserving palm PD in the present are mainly concentrated in the western Amazonia, Chocó, Tropical Andes, Atlantic Forest and Mesoamerica (Figure 3). We observed a spatially highly congruent set of priority areas independent of the period, climate, and dispersal scenarios. (Figures S9 and S10). Under current conditions, most phylogenetic branches were represented by < 40% of their range in the PA network (Figure 3). We found that an increase of just 5% in areas assigned as PAs would double the representation of PD in PAs, from 25% to 51% across the geographical range of phylogenetic branches, and alternative RCPs and dispersal scenarios (Table S5). Additionally, an increase of 17% in area of PAs would, on average, almost triple current protection levels of the geographical range of phylogenetic branches, rising from 25% to 76% (Table S5).

## 4 | DISCUSSION

We evaluated the effectiveness of the existing Neotropical PA network for protecting the evolutionary diversity of an important plant group, the palms, under current and future climatic conditions based on alternative greenhouse gas emission and dispersal scenarios. We found that the upper portion of the Amazon Basin, Tropical Andes and Mesoamerica are important regions for maintenance of palm PD. Although significant losses in phylogenetic diversity inside PAs are expected under future conditions, especially if dispersal is limited (negligible species dispersal scenario), such losses would be diminished under a human-assisted dispersal scenario. Nevertheless, even under the most optimistic climatic and dispersal scenarios, the established PA network performed poorly in safeguarding palm PD under both current and future climate. Even though a modest increase in PAs could considerably improve the protection of palm PD, such gains will not be evenly distributed among the phylogenetic branches.

Dispersal ability is an essential component of species responses to climate change (Travis et al., 2013). We found that dispersal ability would be a crucial factor for determining how palms PD will be affected by climate change, being responsible for the largest variation in PD changes in the future. Notably, it shows that human-assisted dispersal assisting species in colonising distant suitable areas will be important. Many species are unlikely to be unable to track suitable climatic conditions across long distances (Loarie et al., 2009; Roberts & Hamann, 2016) given low dispersal ability and the challenges posed by anthropogenically fragmented landscapes (Dullinger et al., 2015; Hoegh-Guldberg et al., 2008). Species with specialised habitat requirements, low reproductive success, population or dispersal abilities, and species that are overexploited or susceptible to land-use change must be targeted for a human-assisted dispersal strategy (Vitt et al., 2010). Assisted migration consists of several

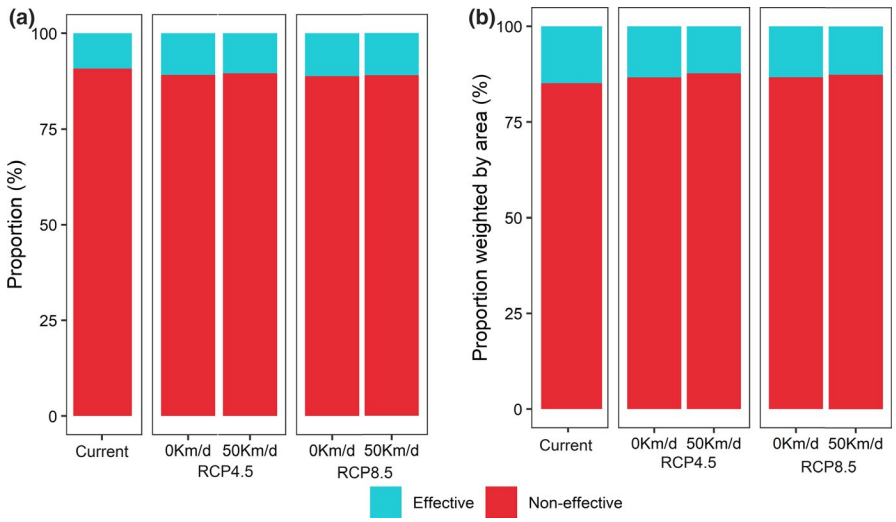


**FIGURE 2** Proportion (a) and proportion weighted by area (b) of effective and non-effective protected areas (PAs; $n = 2,135$) in terms of effectiveness for conservation of phylogenetic diversity of Neotropical palms for current and 2070s conditions under different greenhouse gas emission and dispersal scenarios

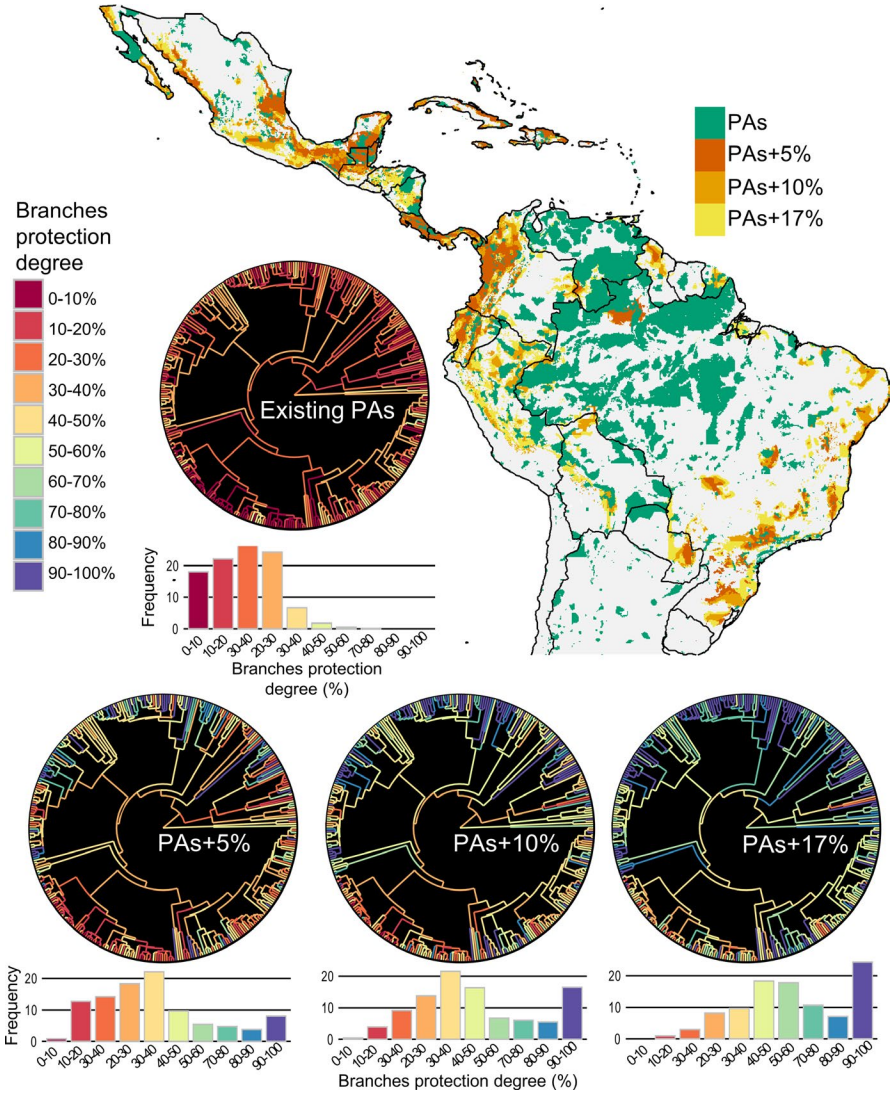


**FIGURE 3** Priority areas for the conservation of the phylogenetic diversity of palms in the Neotropics under current condition, representation level of phylogenetic branches in the established network of protected areas (PAs) and the potential protection gains in PD by expanding PAs according to different priority levels. Priority areas complement the species representation level already achieved in the established network of PAs (green). Expansions of the PA network to 5%, 10% and 17% of the landscape are shown in deep orange, light orange and yellow, respectively. The proportion of phylogenetic branches for different protection classes (legend on the left) is represented by a histogram below each phylogeny. Colours closer to blue mean a higher degree of protection, that is a greater proportion of the geographical extent of a given branch that is protected

steps such as identification of target species, selection of the best-adapted population, selection of individuals or production of propagules, detection of the best location to relocation and monitoring (Charles & Stehlik, 2020; Vitt et al., 2010). Our human-assisted dispersal scenarios may be overly simplistic and optimistic. This could be improved in future research by adding information regarding the ecological aspect of the species (e.g. natural dispersal capacity and population dynamic) and spatial information to help detect the most reliable relocation sites (e.g. accessibility from cities or routes, climate stability and natural cover maintenance). The general success of relying on human-assisted dispersal for helping species to track climate change is uncertain, and a more integrated strategy of conservation is needed (Loss et al., 2011). For instance, integration of assisted dispersal and reforestation and restoration programs, research about seed banks, germination, asexual reproduction and nursery production of Neotropical palms should be on the research agenda, as otherwise assisted dispersal procedures would have limited feasibility.

Our findings highlight that the existing PAs are not effective for protecting this plant family despite its high biological and societal importance, and probably are not enough for protecting many other species as well since the regions with the greatest palm PD are broadly congruent with areas known to harbour the highest PD of other groups (Davies & Buckley, 2011; Voskamp et al., 2017). Neotropical PAs are spatially biased (Baldi et al., 2017) and poorly interconnected (Saura et al., 2017, 2018), probably contributing to the low effectiveness detected here. There are countless palm species under threat that could be cornerstones for the creation of new PAs in the Neotropics, for example *Brahea aculeata*, *Butia purpurascens* and *Ceroxylon echinulatum*, which are used for a wide variety of purposes (Laureto & Cianciaruso, 2017). The ineffectiveness of many PAs does not mean that they are useless because they can protect other groups or other nature components (e.g. peculiar landscapes, biotic communities and ecosystem services), but just that they are not optimally located for protecting the PD of palms. Importantly, our results mean there are many areas with high conservation importance for palms that remain unprotected, reinforcing the need for each nation in the region to increase efforts to create new strategically located PAs.

Our null models identified the countries where PAs protect higher PD than expected by chance. Notably, areas of high PD promote

high ecosystem stability (Cadotte et al., 2012; Craven et al., 2018; Srivastava et al., 2012), as well as guarantee the protection of other components of diversity (e.g. functional and taxonomical). We demonstrated that a strategic expansion of the PA network could derive substantial benefits for conserving the PD of palms (Figure 3; Table S5) while accounting for uncertainties associated with alternative climate models and dispersal scenarios. The identified priority areas can assist in choosing effective PAs for safeguarding the local and regional PD of palm species in the face of climate change. It is important to note that several priority areas are consistent with known hotspots for biodiversity generally and plants specifically, for example such as the Atlantic Forest, Tumbes-Choco-Magdalena, Tropical Andes and Mesoamerica (Mittermeier et al., 2011; Pelletier et al., 2018), reinforcing the importance of such areas for prioritisation of biodiversity conservation efforts. Furthermore, conservation decisions focused on palm species could also benefit animal groups that are inefficiently protected (Pollock et al., 2017; Rosauer et al., 2017). Our spatial prioritisation analyses disregarded the limits of nations, deriving a complete picture for palms conservation by avoiding geopolitical artefacts (Moilanen et al., 2013). Because our conservation analyses were based on biological components and land-use, current priority areas could conflict with socio-economic and political components (such as environmental governance of nations, land acquisition value, human density; Faleiro & Loyola, 2013). Therefore, it would be advisable to include such societal factors in future spatial prioritisation analyses throughout the study area.

There are drivers and government in the regions that deteriorate conservation governance and threaten PA integrity. A clear example of this is the narco-trafficking in some countries of Central America, where narco-funded livestock production causes deforestation outside and within PAs and impact negatively on conservation governance (Devine et al., 2020; Wrathall et al., 2020). Indigenous territories and PAs in Bolivia are under pressure because of policies that allow activities like hydrocarbon exploration, mining, dams, road and agricultural, several of them within PAs (Romero-Muñoz et al., 2019). The current Brazilian government have anti-conservationist policies like a bill to reduce the protection status of indigenous lands to mining activities (Villén-Pérez et al., 2020). Despite these situations, new protected areas across the Neotropics have been created in the last decade, notably as private reserves (e.g. in Argentina, Brazil, Colombia, Mexico and Perú) highlighting civil society's voluntary conservation efforts.

As identified in the present study, important sources of uncertainty include distribution modelling algorithms and dispersal assumptions, reinforcing that conclusions must be carefully drawn from these approaches (Sofaer et al., 2018; Thuiller et al., 2019). Algorithms are recognised as the main uncertainty source in species distribution prediction (Thuiller et al., 2019) with no single approach performing well for all modelling situations (Qiao et al., 2015). Concerning dispersal, our assessment did not consider several factors that could be important for predicting range shifts, for example interspecific variation in dispersal capacity (Eiserhardt et al., 2011), spatiotemporal dynamics in range development, species-specific natural barriers, and species interactions (Cahill et al., 2012; Carter et al., 2018; Wadgymar et al., 2018) as the necessary information does not exist for most of the species analysed here. Nevertheless, we consider our estimates to be broadly robust to these sources of variation as they build on realistic ecological assumptions and state-of-the-art distribution modelling, providing general insights into the potential future consequences of climate change effects on the PD of Neotropical palms.

## 5 | CONCLUSION

The existing PA network in the Neotropics is ineffective for safeguarding palm PD under current climate conditions and probably will remain ineffective in the future, even under the most optimistic climatic and dispersal scenarios. High PD losses are expected inside the PA network under a near-future climate change and negligible large-scale species dispersal. However, higher realised dispersal rates would reduce such losses. The ineffectiveness of many PAs highlights that large areas with high PD are still unprotected. A modest and strategic expansion of the PA network in the upper portion of the Amazon Basin, Tropical Andes and Mesoamerica could strongly improve the conservation of the evolutionary diversity of this key plant family.

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### AUTHORS' CONTRIBUTIONS

SJEV and LMOL conceived the study. SJEV and LMOL collected and cleaned the species occurrence data. SJEV, LMOL, and J-CS defined the procedure used to create ecological niche models. SJEV wrote the code to pre- and post-process ecological niche models and perform null models. BRR and SJEV carried out the spatial prioritisation analysis. All authors drafted the manuscript.

### PEER REVIEW

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### DATA AVAILABILITY STATEMENT

Authors have made available the raster layers of prioritisation analysis in Dryad repository: https://doi.org/10.5061/dryad.6t1g1jwxm

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## BIOSKETCH

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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